

Final Report for the Pilot Study to Assess Current Understanding of Lateral Mixing in the Ocean

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INTRODUCTION

The objective of the pilot study was to assess the state of our understanding of processes contributing to lateral mixing in the ocean on scales of 10 m – 10 km, and their effect on physical and biological variables by conferring with experts in the biological and physical oceanography communities. Our goals were to produce an up-to-date, comprehensive picture of what is understood about small-scale lateral mixing in the ocean, assess what processes are not yet fully understood and require further scrutiny, identify outstanding research directions related to this topic, and make recommendations on how to proceed forward. The pilot study has culminated in the writing of a white paper, entitled “Lateral Mixing at Scales of 10m-10km: A Way Forward”. This white paper includes (i) a summary of the state-of-the-science of small-scale lateral mixing and an assessment of a broad range of observational and numerical (small-scale and regional-scale) perspectives, (ii) the formulation of a challenge to the oceanographic community on this topic, and (iii) a list of recommendations on how to address the challenge with an integrated numerical modeling and field program. A description of the major points addressed in the white paper is given in the following sections.

BACKGROUND

Lateral mixing is one of the most basic oceanographic phenomena affecting the distribution of physical and biological fields throughout the ocean. Yet, it is one of the least understood. The need for a better understanding of the processes controlling small-scale (0.1-10 km) lateral dispersion in the ocean is pressing. Important problems range from quantifying the rates at which nutrients and other dissolved constituents are mixed in and around frontal regions (i.e., mixing fronts, shelf-slope fronts, river plumes), to better understanding of acoustic transmission and losses in coastal regions, to understanding the dynamics and spreading of harmful algal blooms, to correctly parameterizing subgridscale lateral dispersion in regional models. For example, lateral mixing processes contribute to the ‘patchy’ distribution of plankton in the ocean; such patchiness in turn affects predator-prey relationships, ecosystem dynamics, and production, providing a central challenge to biological

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sampling at sea (Martin 2003). Yet even at the most basic level, our knowledge of both the mechanisms responsible for small-scale lateral dispersion and the physical parameters that control them is incomplete. While vertical turbulence closure and the problem of vertical mixing have been the topic of observational, theoretical and numerical studies for decades, relatively little effort has been directed at understanding small-scale horizontal processes in the ocean. A better understanding of lateral dispersion is crucial to many problems of interest to the Navy and society in general, from submarine detection to the development of operational parameterizations of small-scale lateral dispersion based on readily obtained, larger-scale ambient parameters (e.g., Coriolis frequency, mean shear and buoyancy profiles). Such parameterizations are needed for regional-scale numerical models such as the Navy Coastal Ocean Model (NCOM), as well as community-based models such as the Regional Ocean Model System (ROMS) and the Hybrid Coordinate Ocean Model (HYCOM). Presently there are no submesoscale parameterizations for numerical models that handle both biological and physical aspects correctly. Furthermore, observed rates of lateral mixing are typically much larger (by several orders of magnitude) than expected from classical shear dispersion models. In fact, the classical Fickian diffusion model itself does not work in typical coastal ocean conditions, and a new formulation, which takes into account the strong scale dependence of the dispersion is needed.

STATE OF THE COMMUNITY'S UNDERSTANDING

Significant lateral mixing on scales of 10 m – 10 km is observed in coastal and estuarine environments, at sites close to and away from coastlines, in the surface mixed layer, in the stratified interior, as well as in the bottom boundary layer. Active lateral mixing occurs under ocean conditions ranging from relatively quiescent environments such as the inlets of Puget Sound or the New England Shelf to more energetic regions such as Monterey Bay, San Francisco Bay, or in regions with intense mesoscale eddy activity. Observed rates of lateral mixing are typically much larger (by several orders of magnitude) than expected from classical shear dispersion models (Sundermeyer and Ledwell, 2000; Ledwell et al. 1998). One puzzling manifestation of lateral mixing is long-lived thin coherent plankton layers that form in both sheltered and more turbulent environments (Martin, 2003). They can extend for kilometers and persist for days (Rines et al, 2002), and are known to impact acoustic transmission capabilities (Holliday et al, 1998, 2003). While it is speculated that episodic increases in current shear and density gradients play an important role in their creation and destruction, the conditions under which such thin layers form are not currently predictable, and the role of lateral mixing and vertical processes in maintaining or destroying them is not well understood (Donaghay and Osborn, 1997; McManus et al., 2005; Donaghay, 2004).

Lateral mixing is also important in frontal regions, where wind forcing and a variety of instabilities (e.g. mixed-layer, ageostrophic anticyclonic) can transfer energy from the mesoscale to the submesoscale. The result can be intense, localized upwelling/downwelling leading to enhanced biological productivity; satellite images reveal intricate patterns of elongated submesoscale filaments in highly strained regions of mesoscale eddy fields (Munk et al., 2000). Such observations suggest a connection between vertical and horizontal processes and lateral mixing in controlling biological productivity. However, the relative roles of these processes are not understood (Mahadevan, 2006; Mahadevan and Tandon, 2006). Idealized numerical simulations of 2D and geostrophic turbulence, in conjunction with theory, have shed light onto the relationship between strain and vorticity fields, and horizontal mixing, but the effect of stratification remains unclear.

Lateral mixing of momentum is also not well understood. Aside from classical ideas of momentum mixing by eddies, other mechanisms of lateral mixing of momentum have also been proposed, such as

the interaction of internal wave packets with mesoscale strain fields, which leads to a drain of energy from the mesoscales to internal waves (Polzin, 2005). It is unclear whether internal wave packets interact with submesoscale strain in a similar manner, and if so what impact, if any, this might have on lateral mixing. Lateral diffusivity as well as viscosity are often used in numerical models to control the development of unresolved scales. However, these tend to smooth lateral gradients, with the unintended consequence of reducing biological productivity, which tends to be localized in upwelling, sharp-gradient, ageostrophic regions. Presently there are no submesoscale parameterizations for numerical models that handle both biological and physical aspects correctly.

The interaction of lateral mixing with coastal topography is another active research area. In the vicinity of sharp features such as headlands, strong flows can separate and experience significant form drag, generating eddies (Pawlak et al., 2003; Edwards et al., 2004). Drifter studies and numerical model simulations have shown that eddies, once generated, can travel away from the coast, thereby mixing fluid laterally. Longer lived eddies are known to be more efficient at mixing fluid, but what governs their lifetime, especially in stratified conditions, is not fully known. In topographically constrained regions such as estuaries, fluids with different densities are brought together in highly sheared and strained conditions. Identifying the effects of lateral mixing in view of the three-way interaction between straining, vertical mixing and lateral mixing remains a key question (Stacey et al, 2000; Fong and Stacey, 2003). In many cases, both coastal and estuarine, the dispersion of scalar tracers exhibits highly scale-dependent behavior, which cannot be modeled in terms of classical Fickian diffusion. In fact, the Fickian diffusion model does not work in typical coastal ocean conditions, and a new formulation, which takes into account the strong scale dependence of the dispersion needs to be developed.

A recurring theme in all of the above is that submesoscale lateral mixing is either not well understood, or not well described by traditional paradigms of dispersion, or both. For example, small-scale horizontal diffusivities estimated from dye tracer patterns are typically many orders of magnitude larger than expected from shear dispersion (Ledwell et al., 1998, Dale et al., 2006). One potential source for the strong observed dispersion at these scales, is mixing by submesoscale eddies formed during the geostrophic adjustment of well-mixed regions of fluid following internal-wave breaking. Idealized numerical simulations have demonstrated that this process efficiently stirs fluid, but whether it actually occurs in the ocean remains to be established (Sundermeyer and Lelong, 2005). The presence of significant small-scale horizontal and vertical structures has been observed with airborne LIDAR mapping of dye during a pilot study; however, their generation mechanisms are yet unknown (Sundermeyer et al., 2006). Much remains to be done to bring this and other modern observational and modeling approaches to bear on this problem.

In short, the known causes and effects of lateral mixing are varied but they all involve, in some fashion, a connection between vertical and horizontal processes, and between the mesoscale and the submesoscale. Current understanding of lateral mixing is derived from observations of biological and dye tracers, drifters, ADCP arrays and remote sensing techniques, all used in conjunction with process-oriented numerical models. These existing tools will provide the needed framework to further understand the processes and effects of lateral mixing on scales of 10 m – 10 km and their physical/biological implications in a coastal environment.

A CHALLENGE FOR THE OCEANOGRAPHIC COMMUNITY

Given the state of in our present state of knowledge, the overarching challenge to the oceanographic community can be formulated as follows:

Challenge: To understand the processes and effects of dispersion and lateral variability of velocity, density and other biological/chemical tracers at scales ranging from 10 m-10 km in the coastal ocean, and to quantify how the generation, persistence, and breakdown of features associated with this variability relate to mixing at these scales.

This overarching challenge contains many important questions. Given what is known about mesoscale eddies, frontal dynamics, river outflows, internal waves and internal wave breaking, how can lateral tracer dispersion in an energetic, stratified, rotating environment be predicted? Why is the process sometimes rapid and sometimes slow, allowing, for example, the persistence of thin layers of biological organisms? What are the separate and compound roles of vertical and lateral advective processes, mesoscale and submesoscale eddies, mesoscale and submesoscale variability in boundary forcing, internal (or surface) waves, and energy flux from boundary layers in controlling dispersion? Which of these processes constrain the lateral distribution of tracers, especially biological; and for various processes, what links the distribution of these tracers to ocean dynamics at different scales? How do submesoscale processes bridge the gap between the mesoscale and 3-d mixing microscale, and can a common framework for lateral mixing be applied to physics, tracers and biology? Lastly, given the difficulty that numerical models have in reproducing cross-shelf dispersion, what set of observations will contribute toward improvement of model performance?

A framework for addressing these issues through a coordinated, multi-year, multi-disciplinary combined numerical-modeling and field program is described in the following section.

HOW TO MOVE FORWARD

Overarching Themes

In the above assessment of the understanding of submesoscale lateral mixing processes, three overarching themes emerge:

1. interaction between different scales (mesoscale, submesoscale, and microscale);
2. interaction between vertical and horizontal processes;
3. coupling between physical and biological processes.

These three themes in turn lend themselves to several approaches, as outlined below, which could be addressed satisfactorily within a 5-year coordinated research program.

Approaches

Numerical process studies

Given the scope of the problems highlighted above, numerical modeling studies, particularly process-oriented studies are a powerful tool for understanding the underlying, but hitherto still poorly understood dynamics associated with the above three themes. Idealized studies of lateral mixing processes could provide insight, especially in the first year to aid in planning subsequent fieldwork. There are several examples of existing high-resolution models capable of simulating one or more of the identified lateral mixing mechanisms. The models could be set up in idealized configurations, which could then be varied (e.g., turning wind on and off; varying the large-scale current field) in order to gain insight into the lateral mixing process. Existing datasets, for example those collected during the ONR-funded Coastal Mixing and Optics (CMO) or Layered Organization in the Coastal Ocean (LOCO) programs, could set the parameters of the idealized model studies. Model-to-model differences in lateral mixing could be identified with defined metrics such as the spread and filamentation of a simulated dye patch, or vorticity spectra. Prime candidates for process studies include large eddy simulation (LES) models, comprehensive data assimilation, or hindcasting. Regional models could also be useful in interpreting field observations by providing the corresponding larger-scale flow features.

Field studies

Complementing process-oriented numerical simulations, a comprehensive, multi-year field program using a suite of modern observational techniques should also be undertaken to help address a suite of unanswered questions, and to provide insight into the basic structure of mixing at these scales. Such observations, which could draw on results from the initial modeling studies, should capitalize heavily on a suite of new observational technologies. Several new and existing field methods are promising. Tracer studies should be a central piece of the field effort, and could include dye releases as well as natural tracers (e.g. iron, CDOM, or thin layers of dense biota). A strategy of repeat short-term dye releases is probably most practical. In addition to the dispersion of tracers, an important observational goal is the horizontal and vertical strain contributing to mixing. Rapid aircraft mapping of the tracer field (both natural and purposefully released tracers) by airborne LIDAR is essential and could guide adaptive sampling by *in situ* observations. An aircraft platform would also be useful for remote sensing of surface fields such as SST, ocean color, and/or velocity. Lagrangian techniques such as instrumented floats or drifters should also be incorporated into the field study. Eulerian techniques could include a dense array of sensors or adaptively deployed moorings. To study the biological response to lateral mixing, optical or acoustical mapping of biological distributions could also guide sampling.

To serve the overarching themes, the ideal field site fits several criteria. It should be a stratified coastal site with known characteristics from prior research, including active lateral mixing. Nearby locations with relatively weak lateral mixing could provide a useful comparison. The site should not be dominated by other dynamics, such as are important at river mouths or strong fronts. The site should also have relatively easy access for aircraft remote sensing. A biologically productive region, or one in which productivity is known to respond to lateral mixing, would be a good choice.

How the challenge will be addressed by approaches

As described above, an integrated numerical modeling and field program would enable great progress to be made in the understanding of submesoscale lateral mixing processes and the sources of observed horizontal finestructure of physical and biological fields. The above-described suite of Lagrangian drifter and tracer measurements would provide direct observations of horizontal finestructure at unprecedented spatial and temporal scales and resolutions. The finestructure generated by the horizontal and vertical strain fields would further be measured with Eulerian and adaptive sampling measurements. Meanwhile, at larger scales, the mechanisms producing the strain would be assessed with larger-scale field observations. As well, the mixing mechanisms and their effects on lateral dispersion would be isolated with numerical process studies. Finally, the effects of lateral mixing on biological fields could be evaluated using imaging measurements accompanied by field sampling and perhaps coupled modeling. In addition, the same remote sensing and *in situ* observations of biological fields could be used to interpret the physics, and provide further insight into biophysical coupling at these scales.

REFERENCES

- Dale, A. C., M. D. Levine, J. A. Barth, and J. A. Austin, 2006. A dye tracer reveals cross-shelf dispersion and interleaving on the Oregon shelf, *Geophys. Res. Lett.*, **33**, L03604, doi:10.1029/2005GL024959.
- Donaghay, P.L., 2004. Profiling systems for understanding the dynamics and impacts of thin layers of harmful algae in stratified coastal waters. Proceedings of the 4th Irish Marine Biotoxin Science Workshop, 44-53.
- Donaghay, P. L., and T. R. Osborn, 1997. Toward a theory of biological-physical control of harmful algal bloom population dynamics and impacts. *Limnol. Oceanogr.*, **42(5,2)**: 1283-1296.
- Edwards, K. A., P. MacCready, J. N. Moum, G. Pawlak, J. Klymak, and A. Perlin, 2004. Form Drag and Mixing due to Tidal Flow past a Sharp Point. *J. Phys. Oceanogr.*, **34**, 1297-1312.
- Fong, D.A. and M.T. Stacey, 2003: Horizontal dispersion of a near-bed coastal plume, *J. Fluid Mech.*, **49**, 239-267.
- Holliday, D.V., R.E. Pieper, C.F. Greenlaw, and J. J. Dawson, 1998. Acoustical sensing of small-scale vertical structures in zooplankton assemblages, *Oceanography*, **11(7)**: 18-23.
- Holliday, D.V., P.L. Donaghay, C.F. Greenlaw, D.E. McGehee, M.M. McManus, J. M. Sullivan, J.L. Miksis, 2003. Advances in defining fine- and micro-scale pattern in marine plankton. *Aquatic Living Resources*, **16(3)**: 131-136.
- Ledwell, J. R., A. J. Watson, and C. S. Law, 1998. Mixing of a tracer released in the pycnocline. *J. Geophys. Res.* **103**, 21,499-21,529.
- Mahadevan, A., 2006. Modeling vertical motion at ocean fronts: Are nonhydrostatic effects relevant at submesoscales? *Ocean Modelling*, **14**, 222-240.

- Mahadevan, A. and A. Tandon, 2006. An analysis of mechanisms for submesoscale vertical motion at ocean fronts, *Ocean Modelling*, **14**, 241-256.
- Martin, A. P., 2003: Plankton patchiness: the role of lateral stirring and mixing. *Progr. Ocean.*, **57**(2), 125-174..
- McManus M. A., O. M. Cheriton, P. J. Drake, D. V. Holliday, C. D. Storlazzi, P. L. Donaghay and C. E. Greenlaw, 2005. The effects of physical processes on the structure and transport of thin zooplankton layers in the coastal ocean. *Marine Ecol. Progr. Ser.* **301**, 199-215.
- Munk, W., L. Armi, K. Fischer, and F. Zachariasen, 2000. Spirals on the sea: A manifestation of upper ocean stirring. In *Proc. R. Soc. Lond. A* **456**, pp. 1217-1280.
- Pawlak, G., P. MacCready, K. A. Edwards, R. McCabe, 2003. Observations on the evolution of tidal vorticity at a stratified deep water headland. *Geophys. Res. Lett.*, **30** (24), 2234, 10.1029/2003GL018092.
- Polzin, K.L., 2005. How Rossby waves break. Internal wave-mesoscale eddy-Zonal mean interactions, submitted to *J. of Phys. Oceanogr.* Sept. 2005.
- Rines, J. E. B., P. L. Donaghay, M. M. Dekshenieks, J. M. Sullivan and M. S. Twardowski, 2002. Thin Layers and Camouflage: Hidden Pseudo-nitzschia populations in a fjord in the San Juan Islands, Washington, USA. *Mar. Ecol. Progr. Ser.* **225**, 123-137.
- Stacey, M.T., E.A. Cowen, T.M. Powell, E. Dobbins, S.G. Monismith and J.P. Koseff, 2000: Plume dispersion in a stratified, near-coastal flow: measurements and modeling. *Cont. Shelf Res.*, **20**, 637-663.
- Sundermeyer, M. A. and J. R. Ledwell, 2001. Lateral Dispersion over the continental shelf: Analysis of dye-release experiments. *J. Geophys Res.*, **106**, 9,603-9,621.
- Sundermeyer, M. A., and, M. P. Lelong. Numerical simulations of lateral stirring the by the relaxation of diapycnal mixing events. *J. Phys. Oceanogr.*, **35** (12), 2368-2386, 2005.
- Sundermeyer, M. A., E. A. Terray, J. R. Ledwell, A. G. Cunningham, P. E. LaRocque. J. Banic, and W. J. Lillycrop. Three-dimensional mapping of fluorescent dye using a scanning, depth-resolving airborne lidar. *J. Atmos. Ocean. Technol.* , Accepted.